# Chapter 3
# Geology Considerations

## 3-1. General

*a.* The site geology provides the setting for any underground structure. The mechanical properties of the rock describe how the geologic materials deform and fail under the forces introduced by the excavation. The geohydrologic conditions establish the quantity and pressure of water that must be controlled. Once the designer has established estimates and associated uncertainties for these parameters, the performance of the rock mass can be estimated, and the design of an underground structure can proceed.

*b.* The geologic stratigraphy and structure form the framework for exploring and classifying the rock mass for design and construction purposes. This geologic framework subdivides the rock mass into rock types of varying characteristics, delineates geologic boundaries, and provides clues as to geologic or hydrologic hazards. For each type of rock, intact rock properties affect stress-induced modes of behavior, durability and excavation effort, while rock mass properties—greatly affected by discontinuities and weathering—affect opening stability during and after construction.

*c.* This chapter describes the geologic parameters pertinent to the design of underground openings. It discusses the geomechanical properties of the intact rock and the rock mass, in situ stresses in the undisturbed rock mass, effects of weathering and discontinuities such as joints and faults on rock mass performance, and occurrences of groundwater and gases. These parameters form the basis for predicting the performance of underground structures.

## 3-2. Properties of Intact Rocks

*a.* Rocks are natural materials whose composition can be highly variable. They are usually aggregates of mineral particles although a few rocks form as amorphous glasses. Minerals are inorganic substances with unique fixed chemical compositions. The most common minerals found in rocks are given in Table 3-1. They are mainly silicates. Each mineral in a rock has physical, mechanical, and chemical properties that differ from those of other minerals present. The mineralogy of a rock is generally

**Table 3-1**
**Common Minerals**

| Mineral Group | Chemical Composition | Hardness | Color | Other Characteristics |
|---|---|---|---|---|
| Feldspars | Aluminosilicates of potassium (orthoclase feldspar) or sodium and calcium (plagioclase feldspar) with 3-dimensional structures | 6 | White or grey, less commonly pink | Weathers relatively easily |
| Quartz | Silica, chemically very stable | 7 | Colorless | Breaks with conchoidal fracture |
| Clay Minerals | Aluminosilicates with crystal size too small to be seen with a low-powered microscope | 2-3 | Usually white, grey, or black | May occur as sheets that give a characteristic clayey soapy texture |
| Micas | Aluminosilicates of potassium (muscovite mica) or potassium-magnesium-iron (biotite mica) with sheet structures. Relatively stable minerals | 2-3 | Muscovite is colorless; biotite is dark green or brown to black | Break readily along close parallel planes, forming thin flakes on weathering<br><br>Muscovite often twinkles in flakes on rock surface |
| Chlorite | Chemically a hydrous iron-magnesium aluminosilicate | 2-2.5 | Green | Soft, breaks readily and forms flakes |
| Calcite | Chemical composition $CaCO_3$ | 3 | Ferric iron ores are red and brown; ferrous iron ores are green and grey | |
| Iron Ores | Oxides, Hematite ($Fe_2O_3$); carbonates; pyrite ($FeS_2$) | 5-7 | Dark green, brown to black | |
| Ferromagnesium Minerals | Chemically complex calcium and sodium aluminosilicates rich in iron and magnesium (hornblende, augite, olivine) | | | |

**Table 3-2**
**Moh's Scale for Measuring the Hardness of Minerals**

| Standard Mineral | Hardness Scale | Field Guide |
|---|---|---|
| Talc | 1 | |
| Gypsum | 2 | |
| | | Finger nail |
| Calcite | 3 | |
| | | Copper penny |
| Fluorite | 4 | |
| Apatite | 5 | Iron nail |
| | 5.5 | Window glass |
| Orthoclase feldspar | 6 | Penknife |
| Quartz | 7 | Steel file |
| Topaz | 8 | |
| Corundum | 9 | |
| Diamond | 10 | |

determined by examination of thin sections in microscope. However, the Moh's scale of hardness (Table 3-2) provides a field procedure that can assist in identifying minerals according to their hardness and in characterizing rocks.

*b*. Mineral characteristics influence the engineering properties of a rock, especially when the mineral forms a significant part of the rock. Anhydrous silicates (feldspars, quartz, hornblende, augite, olivine) are considerably harder and stronger than most other common minerals and can affect the strength of a rock, its cuttability, and how it deforms. Large amounts of a relatively soft mineral such as mica or calcite can result in rapid breakdown due to weathering processes. Minerals with marked cleavage can cause anisotropy in a rock. However, since individual mineral particles are small, each particle usually has little direct influence on the mechanical properties of the rock as a whole. Although the mineralogy of a rock will influence the behavior of a rock, mechanical tests on rock samples are generally needed to define the engineering properties of rocks.

*c*. Rocks are broadly classified into three major groups based on their mode of origin:

(1) *Igneous rocks*. These form from the solidification of molten material that originates in or below the earth's crust. The composition depends on the kind of molten material (magma) from which it crystallizes, and its texture depends on the rate at which the material cools. Slow rates of cooling promote larger crystal-sized rock (pegmatite), whereas fast-cooling rates produce fine crystallized rock (basalt, rhyolite), or even amorphous glasses (obsidian).

(2) *Sedimentary rocks*. These form from cemented aggregates of transported fragments of rock (sandstone, siltstone, mudstone); from the accumulation of organic debris such as shell fragments and dead plants (limestone, coal); or minerals that are chemically precipitated (rock salt, gypsum, limestone).

(3) *Metamorphic rocks*. These form deep in the earth from preexisting rocks of all types in response to increases in temperature or pressure or both (gneiss, schist, slate, marble, quartzite). The composition of the metamorphosed rock depends on the original material and the temperature and pressure; its texture reflects the deformational forces.

*d*. Within each of these groups, separate classification systems have been developed in terms of mineral composition, grain size, and texture. The systems used for the study of geology are rather elaborate for engineering purposes, and simplifications are in order for engineering applications. Clayton, Simons, and Matthews (1982) proposed a simplified system for rock identification based on origin and grain size for igneous, sedimentary, and metamorphic rocks that provides a useful framework, within which the engineer can work. Their classification scheme for igneous rocks is given in Table 3-3 and is based on crystal size. Because crystal size is dependent on rate of cooling, the rock formation’s mode of origin can be determined. The classification scheme for sedimentary rocks is given in Table 3-4. This classification is based on the mode of deposition and the chemical composition of the rocks as well as particle size. The classification scheme for metamorphic rocks is given in Table 3-5. It is based on grain structure and mineralogy.

*e*. Intact rock material contains grains and intergranular pores filled with air and water. The relative volumes and weights of these three constituents determine porosity, density, and saturation. The porosity of the rock has an important effect on the permeability and strength of the rock material. Other factors, such as the chemical compositions of the grains and cementation, will affect how easily it weathers or disintegrates on exposure and how abrasive it will be to cutting tools during excavation. For example,

**Table 3-3**
**Igneous Rocks**

| | Acid | Intermediate | Basic | Ultrabasic |
|---|---|---|---|---|
| Grain Size | Light-Colored Rocks | Light/Dark-Colored Rocks | Dark-Colored Rocks | Dark-Colored Rocks |
| Very coarse grained<br>60 mm | Rock consists of very large and often well-developed crystals of quartz, feldspar mica, and frequently rare minerals<br>**PEGMATITE** | | | |
| Coarse grained | At least 50% of the rock is coarse grained enough to allow individual minerals to be identified. | | | Rock is coarse grained and dark in color (dull green to black) with a granular texture. It contains olivine and augite in abundance but no feldspars<br>**PERIDOTITE** |
| 2 mm | Rock is light colored with an equigranular texture (majority of grains approximately the same size) and contains > 20% quartz with feldspar in abundance.<br>**GRANITE** | Rock may be medium to dark in color with more or less equigranular texture and contains < 20% quartz with feldspar and horneblende in abundance.<br>**DIORITE** | Rock is dark colored and often greenish with abundant plagioclase (about 60%) and augite together with some olivine. The rock usually feels dense.<br>**GABBRO** | |
| Medium grained | At least 50% of the rock is medium grained. Crystal outlines are generally visible with the aid of a hand lens, but individual minerals may be difficult to identify. | | | Rock is greyish green to black with a splintery fracture when broken and generally feels soapy or waxy to the touch. It is often crisscrossed by veins of fibrous minerals and/or banded.<br>**SERPENTINITE** |
| 0.06 mm | Rock is similar in appearance to granite, but the crystals are generally much smaller.<br>**MICRO-GRANITE** | Rock is similar in appearance to diorite, but crystals are generally much smaller.<br>**MICRO-DIORITE** | Rock is similar in appearance and often greenish with a granular texture. Individual minerals may be difficult to identify. The rock usually feels dense.<br>**DOLERITE** | |
| Fine grained | At least 50% of the rock is fine grained. Outlines of crystals are not usually visible even with the aid of a hand lens. All rocks in this category may be vesicular. | | | |
| | Rock is light colored (often pale reddish brown or pinkish grey) and may be banded.<br>**RHYOLITE**<br>Rock is light colored with a very low specific gravity and highly vesicular.<br>**PUMICE** | Rock is medium to dark in color (shades of grey, purple, brown, or green) and frequently porphyritic.<br>**ANDESITE** | Rock is black when fresh and becomes red or green when weathered. The rock is often vesicular and/or amygdaloidal.<br>**BASALT** | |
| Glassy | Rock is glassy and contains few or no phenocrysts. It is often black in color and has a characteristic vitreous luster and conchoidal fracture.<br>**OBSIDIAN**<br>Rock is glassy and contains few or no phenocrysts. It may be black, brown, or grey in color with a characteristic dull or waxy luster.<br>**PITCHSTONE** | | | |

clay-bearing rocks (shales and mudstones) can swell or disintegrate (slake) when exposed to atmospheric wetting and drying cycles. Typical geotechnical parameters of intact rock are shown in Table 3-6.

*f.* The engineering properties of a rock generally depend not only on the matrix structure formed by the minerals but also imperfections in the structure such as voids (pore space), cracks, inclusions, grain boundaries, and weak particles. Pore spaces are largely made up of continuous irregular capillary cracks separating the mineral grains. In the case of igneous rocks, a slow-cooling magma will make a relatively nonporous rock, whereas a rapidly cooling lava particularly associated with escaping gases will yield a porous rock. In sedimentary rocks,

**Table 3-4**
**Sedimentary Rocks**

| Group | Detrital Sediments Bedded | | Pyroclastic Sediments | Chemical and Organic Sediments<br>Bedded | <br>Massive Bedded |
|---|---|---|---|---|---|
| Composition and Texture | Quartz, rock fragments, feldspar, and other minerals. | At least 50% of rock is comprised of carbonate minerals (rocks usually react with dilute HCl). | At least 50% of grains are fine-grained volcanic material.<br>Rocks often composed of angular mineral or igneous rock fragments in a fine-grained matrix. | Crystalline carbonate rocks depositional texture not recognizable.<br>Fabric is nonclastic. | Depositional textures often not recognizable. |
| Grain Size<br><br>Coarse grained<br><br>2 mm | Rock is composed of more or less rounded grains in a finer grained matrix:<br>**CONGLOMERATE**<br><br>Rock is composed of angular or subangular grains in a finer grained matrix:<br>**BRECCIA** | **CALCI-RUDITE** | Rock is composed of:<br>(i) Rounded grains in a fine-grained matrix:<br>**AGGLOMERATE**<br><br>(ii) Angular grains in a fine-grained matrix:<br>**VOLCANIC BRECCIA** | | Rock is crystalline, salty to taste, and may be scratched with a finger nail:<br>**HALITE** (rock salt)<br><br>Rock is crystalline and may be scratched with the finger nail. Grains turn into a chalky white substance when burned for a few minutes.<br>**GYPSUM** |
| Medium grained<br><br>0.06 mm | Rock is composed of:<br>(i) mainly mineral and rock fragments:<br>**SANDSTONE**<br><br>(ii) 95% quartz. The voids between the grains may be empty or filled with chemical cement:<br>**QUARTZ SANDSTONE**<br><br>(iii) 75% quartz and rock fragments and up to 25% feldspar (grains commonly angular). The voids may be empty or filled with chemical cement: **ARKOSE**<br><br>(iv) 75% quartz and rock fragments together with 15% + fine detrital material:<br>**ARGILLACEOUS SANDSTONE** | **CALCI-ARENITE** | Rock is composed of mainly sand-sized angular mineral and rock fragments in a fine-grained matrix:<br>**TUFF** | Rock is crystalline and composed of calcium carbonate (>90%) - reacts violently with HCl.<br>**LIMESTONE**<br><br>Rock is crystalline and may show a yellowish coloration and/or the presence of voids - reacts mildly with cold dilute HCl.<br>**DOLOMITIC LIMESTONE** | Rock is crystalline, colorless to white, frequently with a bluish tinge. It is harder than gypsum and has three orthogonal cleavages:<br>**ANHYDRITE**<br><br>Rock is black or brownish black and has a low specific gravity (1.8-1.9). It may have a vitreous luster and conchoidal fracture and/or breaks into pieces that are roughly cuboidal<br>**COAL** |

*(Continued)*

**Table 3-4 (Concluded)**

| Group | Detrital Sediments Bedded | | Pyroclastic Sediments | Chemical and Organic Sediments: Bedded | Chemical and Organic Sediments: Massive Bedded |
|---|---|---|---|---|---|
| Composition and Texture | Quartz, rock fragments, feldspar, and other minerals. | At least 50% of rock is comprised of carbonate minerals (rocks usually react with dilute HCl). | At least 50% of grains are fine-grained volcanic material. Rocks often composed of angular mineral or igneous rock fragments in a fine-grained matrix. | Crystalline carbonate rocks depositional texture not recognizable. Fabric is nonclastic. | Depositional textures often not recognizable. |
| Fine grained<br><br>0.002 mm<br><br>Very fine grained | Rock is composed of at least 50% fine-grained particles and feels slightly rough to touch: **SILTSTONE**<br><br>Rock is homogeneous and fine grained. Feels slightly rough to smooth to touch: **MUDSTONE**<br><br>Rock has same appearance and feel as mudstone but reacts with dilute: **CALCAREOUS MUDSTONE**<br><br>Rock is composed of at least 50% very fine-grained particles and feels smooth to the touch: **CLAYSTONE**<br><br>Rock is finely laminated and or fissile. It may be fine or very fine grained: **SHALE** | **CALCI-SILTITE**<br><br>**CHALK** (bioclastic)<br><br>**CALCI-LUTITE** | Rock is composed of silt-sized fragments in a fine-grained matrix. Matrix and fragments may not always be distinguished in the hand specimen:<br><br>**FINE-GRAINED TUFF**<br><br>**VERY FINE-GRAINED TUFF** | Rock is crystalline and composed of magnesium carbonate (>90%). When small chip of rock is immersed in dilute HCl, there is no immediate reaction; but there is a slow formation of $CO_2$ beads on the surface of chip:<br><br>**DOLOMITE** | Rock is black or various shades of gray and breaks with a characteristic conchoidal fracture affording sharp cutting edges. The rock cannot be scratched with a penknife: **FLINT**<br><br>Rock has a similar appearance and hardness as flint but breaks with a more or less flat fracture: **CHERT** |

**Table 3-5**
**Metamorphic Rocks**

| Fabric Grain Size | Foliated | Massive |
|---|---|---|
| | Rock appears to be a complex intermix of metamorphic schists and gneisses and granular igneous rock. Foliations tend to be irregular and best seen in field exposure: **MIGMATITE** | Rock contains randomly oriented mineral grains. (Fine to coarse grained. Foliation, if present is essentially a product of thermal metamorphism associated with igneous intrusions and is generally stronger than the parent rock: **HORNFELS** |
| | Rock contains abundant quartz and/or feldspar. Often the rock consists of alternating layers of light-colored quartz and/or feldspar with layers of dark-colored biotite and hornblende. Foliation is often best seen in field exposures: **GNEISS** | Rock contains more than 50-percent calcite (reacts violently with dilute HCl), is generally light in color with a granular texture: **MARBLE** |
| Coarse grained | | |
| | Rock consists mainly of large platy crystals of mica showing a distinct subparallel or parallel preferred orientation. Foliation is well developed and often nodulose: **SCHIST** | If the major constituent is dolomite instead of calcite (dolomite does not react immediately with dilute HCl), then the rock is termed: **DOLOMITIC MARBLE** |
| 2 mm | | |
| Medium grained | Rock consists of medium- to fine-grained platy, prismatic or needlelike minerals with a preferred orientation. Foliation is slightly nodulose due to isolated larger crystals that give rise to spotted appearance: **PHYLLITE** | Rock is medium to coarse grained with a granular texture and is often banded. This rock type is associated with regional metamorphism: **GRANULITE** |
| 0.06 mm | | |
| Fine grained | Rock consists of very fine grains (individual grains cannot be recognized in hand specimen) with a preferred orientation such that the rock splits easily into thin plates: **SLATE** | Rock consists mainly of quartz (95 percent) grains that are generally randomly oriented giving rise to a granular texture: **QUARTZITE (META-QUARTZITE)** |

porosity will depend largely on the amount of cementing materials present and the size of grading and packing of the granular constituents. Ultimate strength of the rock will depend on the strength of the matrix and the contact between the grains.

## 3-3. Faults, Joints, and Bedding Planes

*a*. Physical discontinuities are present in all rock masses. They occur as a result of geological activities. Rock masses and their component discontinuities can be described by the following principal methods:

- Outcrop description.
- Drill core and drill hole description.
- Terrestrial photogrammetry.

*b*. Table 3-6 provides descriptions of the most commonly encountered discontinuities. The discontinuities introduce defects into the rock mass that alter the properties of the rock material. The mechanical breaks in the rock have zero or low tensile strengths, increase rock deformability, and provide more or less tortuous pathways for water to flow. Unless rock properties are established at a scale that includes representative samples of these defects within the test specimen, the results are not representative of the in situ rock. Therefore, parameters derived from

**Table 3-6**
**Classification of Discontinuities for Particular Rock Types**

| Rock or Soil Type | Discontinuity Type | Physical Characteristics | Geotechnical Aspects | Comments |
|---|---|---|---|---|
| Sedimentary | Bedding planes/ bedding plane joints | Parallel to original deposition surface and making a hiatus in deposition. Usually almost horizontal in unfolded rocks. | Often flat and persistent over tens or hundreds of meters. May mark changes in lithology, strength, and permeability. Commonly close, tight, with considerable cohesion. May become open due to weathering and unloading. | Geological mappable and, therefore, may be extrapolated providing structure understood. Other sedimentary features such as ripple marks and mud-cracks may aid interpretation and affect shear strength. |
| | Slaty cleavage | Close parallel discontinuities formed in mudstones during diagenesis and resulting in fissility. | | |
| | Random fissures | Common in recent sediments probably due to shrinkage and minor shearing during consolidation. Not extensive but important mass feature. | Controlling influence for strength and permeability for many clays. | Best described in terms of frequency. |
| Igneous | Cooling joints | Systematic sets of hexagonal joints perpendicular to cooling surfaces are common in lavas and sills. Larger intrusions typified by doming joints and cross joint. | Columnar joints have regular pattern so are easily dealt with. Other joints often widely spaced with variable orientation and nature. | Either entirely predictable or fairly random. |
| Metamorphic | Slaty cleavage | Closely spaced, parallel, and persistent planar integral discontinuities in fine-grained strong rock. | High cohesion where intact but readily opened to weathering or unloading. Low roughness. | Less mappable than slaty cleavage but general trends recognizable. |
| Applicable to all rocks | Tectonic joints | Persistent fractures resulting from tectonic stresses. Joints often occur as related groups or “sets.” Joint systems of conjugate sets may be explained in terms of regional stress field. | Tectonic joints are classified as “shear” or “tensile” according to probable origin. Shear joints are often less rough that tensile joints. Joints may die out laterally resulting in impersistence and high strength. | May only be extrapolated confidently where systematic and where geological origin is understood. |
| | Faults | Fractures along which displacement has occurred. Any scale from millimeters to hundreds of kilometers. Often associated with zones of sheared rock. | Often low shear strength particularly where slickensided or containing gouge. May be associated with high groundwater flow or act as barriers to flow. Deep zones of weathering occur along faults. Recent faults may be seismically active. | Mappable, especially where rocks either side can be matched. Major faults often recognized as photo lineations due to localized erosion. |
| | Sheeting joints | Rough, often widely spaced fractures; parallel to the ground surface; formed under tension as a result of unloading. | May be persistent over tens of meters. Commonly adverse (parallel to slopes). Weathering concentrated along them in otherwise good quality rock. | Readily identified due to individuality and relationship with topography. |
| | Lithological boundaries | Boundaries between different rock types. May be of any angle, shape, and complexity according to geological history. | Often mark distinct changes in engineering properties such as strength, permeability, and degree and style of jointing. Commonly form barriers to groundwater flow. | Mappable allowing interpolation and extrapolation providing the geological history is understood. |

Note: From A. A. Afrouz, 1992, *Practical Handbook of Rock Mass Classification Systems and Modes of Ground Failure.*

laboratory testing of intact specimens must be used with care for engineering applications.

*c*. The mechanical behavior of intensely fractured rock can sometimes be approximated to that of a soil. At the other extreme, where the rock is massive and the fractures confined, the rock can be considered as a continuous medium. More often, rock must be regarded as a discontinuum. The mechanical properties of discontinuities are therefore of considerable relevance. Roughness, tightness, and filling can control the shear strength and deformability of fractures. Even a tight weathered layer in a joint can considerably reduce the strength afforded by tightly interlocking roughness asperities. Discontinuities that persist smoothly and without interruption over extensive areas offer considerably less resistance to shearing than discontinuities of irregular and interrupted patterns. The orientation of fractures relative to the exposed rock surface is also critical in determining rock mass stability. Fracture spacing is important since it determines the size of rock blocks.

*d*. The International Society of Rock Mechanics (ISRM) Commission on Testing Methods has defined 10 parameters to characterize the discontinuities and allow their engineering attributes to be established. These are as follows:

(1) *Orientation*. Attitude of discontinuity in space. The plane of the discontinuity is defined by the dip direction (azimuth) and dip of the line of steepest declination in the plane of the discontinuity.

(2) *Spacing*. Perpendicular distance between adjacent discontinuities. This normally refers to the mean or modal spacing of a set of joints.

(3) *Persistence.* Discontinuity trace length as observed in an exposure. This may give a crude measure of the areal extent or penetration length of a discontinuity.

(4) *Roughness*. Inherent surface roughness and waviness relative to the mean plane of a discontinuity. Both roughness and waviness contribute to the shear strength. Large waviness may also alter the dip locally.

(5) *Wall strength.* Equivalent compression strength of the adjacent rock walls of a discontinuity. This strength may be lower than the rock block strength due to weathering or alteration of the walls. This may be an important component of the shear strength if rock walls are in contact.

(6) *Aperture.* Perpendicular distance between adjacent walls of a discontinuity in which the intervening space is air or water filled.

(7) *Filling*. Material that separates the adjacent rock walls of a discontinuity and that is usually weaker than the parent rock. Typical filling materials are sand, clay, breccia, gouge, and mylonite. Filling may also be thin mineral coatings that heal discontinuities, e.g., quartz and calcite veins.

(8) *Seepage*. Water flow and free moisture visible in individual discontinuities or in the rock mass as a whole.

(9) *Number of sets*. The number of joint sets comprising the intersecting joint system. The rock mass may be further divided by individual discontinuities.

(10) *Block size*. Rock block dimensions resulting from the mutual orientation of intersecting joint sets and resulting from the spacing of the individual sets. Individual discontinuities may further influence the block size and shape.

*e*. The ISRM has suggested quantitative measures for describing discontinuities (ISRM 1981). It provides standard descriptions for factors such as persistence, roughness, wall strength, aperture, filling, seepage, and block size. Where necessary, it gives suggested methods for measuring these parameters so that the discontinuity can be characterized in a manner that allows comparison.

*f*. Rock mass discontinuities more often than not control the behavior of the rock mass. Discontinuities can form blocks of rock that can loosen and fall onto a tunnel if not properly supported. Discontinuities in unfavorable directions can also affect the stabilities of cut slopes and portal areas.

*g*. For important structures, major discontinuities should be mapped and their effect on the structure analyzed. Additional ground support may be required to prevent particular blocks of rock from moving. It is sometimes appropriate to reorient an important structure, such as a powerhouse or a major cut, so as to minimize the effect of discontinuities.

*h*. It is usually not possible to discover all important discontinuities. Mapping of outcrops and oriented coring can be used to obtain statistical descriptions of joint patterns for analysis. Outcrops and cores can also be used to obtain fracture frequencies (number of fractures per meter or foot) or average spacings. The ratio between fracture spacing and tunnel dimension or room span indicates whether the rock mass will behave more like a continuum or a discontinuum.

*i*. The most common measure of the intensity of rock mass discontinuities is the Rock Quality Designation (RQD), defined as the core recovery using NX core, counting only sound pieces of core longer than 100 mm (4 in.) (see Chapter 4). The RQD measure is employed to evaluate tunnel and slope stability, to estimate ground support requirements empirically, and to furnish correlations between intact rock and rock mass strength and deformation modulus.

## 3-4. Weathering

*a*. Exposed rock will deteriorate with time when exposed to the weather. The elements most critical to the weathering process are temperature and water, including water seeping through the ground. The weathering process involves both physical disintegration—the mechanical breakdown of rock into progressively smaller pieces—and chemical decomposition, resulting from alteration and replacement of the original mineral assemblage with more geochemically stable minerals, such as clay minerals and grains of quartz.

*b*. Freeze-thaw cycles are important physical disintegration mechanisms, occurring in many climatic environments. Diurnal and annual temperature changes also play a role. Fractures and bedding planes in the rock mass are weakness planes where there is easy access for water, naturally occurring acids, plant roots, and microbes. Therefore, the weathering process is greatly accelerated along discontinuities. As an example, limestone in a wet environment will dissolve by the action of carbonic acid and can form deep crevasses filled with weathering products or underground caverns, following the trend of faults and joints. Clay-filled joints with altered joint walls can be found at great depth where moving groundwater has had access.

*c*. In some environments the weathering products are or have been removed by erosional processes such as slides or streamflow. Glacial action can sweep the bedrock surface clean of weathering products and leave sound rock behind. Where weathering products remain in place, saprolite and residual soil will form. The saprolite retains many physical characteristics of the parent rock, including the texture, interparticle cohesion, and relic seams and joints. The behavior of such material can be intermediate between soil and rock. Clay infilling of cracks and joints in saprolite is often slickensided and has a low resistance to sliding, especially when wet.

*d*. The weathering profile is typically very irregular, because the discontinuities favor deep weathering as opposed to the solid, intact blocks. As a result, the top of weathered and sound rock below a saprolite will vary greatly in elevation, and boulders of partly weathered or nearly sound rock will be found within the saprolite.

*e*. The characteristics of the weathered zone is dependent on the parent rock, but even more dependent on the climate. Wet tropical climates favor deep weathering profiles; moderately wet, temperate climates in high-relief terrains favor the development of steep slopes of fresh rock, alluvial deposits, and talus. This interplay between weathering, mineralogy, and geomorphology makes it difficult to predict weathering products and profiles. Where these features and the elevation of the top of sound rock are important for an underground project, experienced geologists should provide an interpretation of the impact of these characteristics on the tunnel design.

## 3-5. Geohydrology

Almost all underground structures have to deal with groundwater. Water inflow during construction must be accommodated, and permanent structures may have to be made nominally watertight or designed for controlled drainage. When met unexpectedly, massive groundwater inflow can have a severe impact on construction and may require extraordinary measures for the permanent structure. It is, therefore, important to predict the occurrence and extent of groundwater and assess the effect of groundwater on the underground structure as part of site explorations. Methods of exploring the groundwater regime are discussed in Chapter 4, but methods of inflow analysis are presented in Section 3-5.e. This section gives a brief description of geologic and geohydrologic features of particular interest for tunneling.

*a*. *Occurrence of groundwater*. Groundwater is found almost everywhere below the ground surface. The hydrologic cycle includes evaporation of surface water, transport by the winds, and precipitation. Some water falling on the ground runs off in creeks and rivers, some evaporates directly or through the pores of plants, and some infiltrates and becomes a part of the body of groundwater. A tunnel or shaft will act as a sink or well unless made essentially watertight. Such an opening will disturb the groundwater regime, accept groundwater inflow, and gradually draw down the groundwater table or reduce porewater pressures in the surrounding aquifer until a new equilibrium is obtained where inflow into the opening matches recharge at the periphery of the zone of influence. In the process, groundwater flows are often reversed from their natural directions, and aquifer release areas may become recharge areas.

*b. Important geologic factors and features.*

(1) For a tunnel, what is most important during construction is the instantaneous water inflow at any given location and the reduction of inflow with time. For the finished structure, the long-term inflow rates, as well as groundwater pressures around the structure, are important. The geologic features controlling these effects can be summarized as follows:

(a) The permeability of the rock mass (aquifer, water-bearing seam, shatter zone) controls the rate of flow at a given head or gradient.

(b) The head of water above the tunnel controls the initial flow gradient; the head may diminish with time. The head of water may also control external water pressures on the finished structure.

(c) The reservoir of water available to flow into the tunnel controls the duration of water inflow or the decrease of inflow with time.

(d) For the steady-state condition, groundwater recharge controls long-term water inflows.

(e) Groundwater barriers are aquitards or aquicludes of low permeability and may isolate bodies of groundwater and affect the volumes of water reservoir.

(2) Porous flow occurs in geologic materials with connected pores and where joints or other discontinuities are closed, or widely spaced, so that they do not control the flow. Examples include most unconsolidated sediments (silts, sands, gravels) and many sedimentary rocks (siltstone, sandstones, conglomerates, and other porous rocks with few or closed discontinuities). The permeability of such materials can be estimated with reasonable accuracy by packer tests in boreholes. Characterization of unconsolidated materials is often carried out using large-scale pumping tests with observation wells to measure drawdown as a function of pumping rates.

(3) Fracture flow dominates in geologic materials with low intact-rock permeability and porosity, most igneous and metamorphic rocks, and sedimentary rocks including shales, limestones, and dolomites. Fracture flow is extremely difficult to classify, characterize, and predict due to the innate variability of fractures in nature.

(4) Flow through an open fracture can be calculated theoretically, assuming parallel faces of the fracture. The flow would increase, for the same gradient, with the cube of fracture aperture. Real joints have widely varying apertures, however, and are usually partly closed, and the bulk of the flow follows intricate channels of least resistance. This phenomenon is called flow channeling. It is estimated that, in a typical case, 80 percent of the fractures do not contribute significantly to the flow, and 90 percent of the flow channels through about 5 percent of the fractures. The distribution of fracture apertures measured in the field is often highly skewed or log-normal—with small apertures dominating—yet most of the flow is through the high-aperture fringe of the distribution. It is, therefore, considered that even extensive fracture mapping (on exposures or in boreholes) will not facilitate an accurate prediction of water inflows into underground openings.

(5) Direct measurement of water flows under a gradient in a packer test is a more reliable means to characterize hydrologic characteristics of a fractured rock mass. Such tests result in equivalent values of permeability, combining effects of all fractures exposed. Even for these types of tests, however, the likelihood of intercepting the small percentage of fractures that will carry most of the flow is small, and a large number of tests are required to obtain adequate statistical coverage.

(6) When fractures are widely spaced relative to the size of the underground opening, significant water flow will occur through individual fractures. This type of inflow is highly unpredictable. On the other hand, the amount of water stored in an individual fracture is small, and flow will decrease rapidly with time unless the fracture receives recharge at close range.

(7) With more closely spaced fractures (5 to 50 fractures across the opening), a few fractures are still likely to dominate the water flow, and the inflow may be predicted, however inaccurately, on the basis of a sufficient number of packer tests.

*c. Hydrologic characteristics of some geologic environments.* It is beyond the scope of this manual to describe all aspects of the hydrology of geologic media. This section describes a brief selection of geologic environments, with emphasis on consolidated (rock-like) materials rather than on unconsolidated aquifers.

(1) *Igneous and Metamorphic Rocks*.

(a) These rocks almost always have low porosity and permeability, and water occurs and flows through fractures in the rock. These rock types include, among others, granite, gneiss, schist and mica schist, quartzite, slate, and some ores. Some porous flow can occur in highly altered rock in weathering zones.

(b) As a rule, the aperture of joint and fracture openings and the number of fractures or joints decrease with depth below ground due to the increase of compressive stresses with depth. However, because of the typically great strength of most of these rocks and their resistance to creep, fractures and faults can bridge and stand open even at great depth. High-water inflows have been seen in mines and in power tunnels and other tunnels many hundred meters deep (see Box 3-1).

(2) *Sedimentary rocks (consolidated)*.

(a) These include conglomerates, sandstones, siltstones, shales, mudstones, marls, and others. Most of these rock types can have a high porosity (10-20 percent), but only the coarser grained of these (conglomerate, sandstone, some siltstones) have an appreciable permeability in the intact state. Thus, the coarser rocks can experience porous flow or fracture flow, or both, depending on the character of fracturing. Flow through the finer grained sediments, however, is essentially fracture flow.

(b) Fractures in the softer sedimentary rocks are more likely to close with depth than in the igneous and metamorphic rocks. In layered sediments, many joints are short and do not contribute much to water flow. Joints are often particularly numerous in synclines and anticlines as compared with the flanks of folds.

(3) *Volcanic rocks*.

(a) Basalts and rhyolites are often laced with numerous fractures due to cooling during the genesis of these rocks. Most of the water from these formations, however, comes from ancillary features. Plateau basalts are formed in layers with vesicular and brecciated material on top of each layer. Sometimes interlayer weathering and deposition is found. Hawaiian basalt typically follows sequences of pahoehoe, lava, and clinkers. Some of the interlayers can carry immense amounts of water.

(b) Basalt flows also feature large tubes created when liquid lava emptied out from under already hardened lava, as well as other voids such as those left behind trees inundated by the lava flow.

(c) Formations such as welded tuff can be highly vesicular and porous, and contain numerous cooling fractures. Thus, both porous and fracture flow can occur.

(4) *Effects of faults and dikes*.

**Box 3-1. Case History: San Jacinto Tunnel, California**

The San Jacinto water tunnel was completed in 1939 for The Metropolitan Water District of Southern California as part of the Colorado Aqueduct project. The 6-m-diam, 21-km-long tunnel was excavated through mostly granitic rocks with zones of metamorphic rock (mica schist, quartzite, marble) at an average depth of about 450 m. Four major faults and about 20 minor faults or fractures were encountered. There were 8 or 10 instances when peak flows of 1,000-1,100 l/s (15,000 gpm) were experienced, with estimated maximum pressures of up to 4.2 MPa (600 psi) but more commonly at 1-2.5 MPa (150-350 psi).

The large surges of inflow usually occurred when tunneling through impermeable major fault zones, notably the Goetz Fault, which held back compartments of groundwater under high head. Another fault, the McInnes Fault, was approached by tunneling from both sides. Drainage into the Goetz Fault and other faults had depleted the reservoir. This resulted in an inflow less than 6 l/s (100 gpm) when the McInnes Fault was crossed.

It was estimated that the tunnel job had depleted some 155,000 acre-feet of water from the aquifers; springs were affected at a distance of 5 km (3 mi).

Source: The Metropolitan Historical Record, 1940.

(a) Small faults are often the source of fracture flow into tunnels. Larger faults or shear zones have been known to produce water inflow of the order of 3,600 l/s (50,000 gpm). The permeability of the geologic material in a shear zone can be highly variable, depending on whether the zone contains mostly shattered and sheared rock or large quantities of less permeable clay gouge or secondary depositions. In many cases, faults act as a barrier between two hydrologic regions. This happens when the fault zone material is less permeable than the adjacent, relatively permeable geologic material, or when a fault offsets less permeable strata against aquifers. Thus, for one reason or another, formation water pressures can be much higher on one side of a fault than the other. Tunneling through a fault from the low-pressure side can result in sudden and unexpected inflow of water.

(b) Many geologic environments are laced with dikes. The original formation of the dikes often disturbed and fractured the host material, and locally the permeability can be many times larger than the main body of the rock mass. On the other hand, the dike material, if not badly fractured, can be tight and form a groundwater barrier much like many faults. Examples of dikes acting as water barriers abound in Hawaii, where dikes crossing very pervious clinker layers can form adjacent compartments with widely differing groundwater levels.

(5) *Interface between rock and overburden*. Since bedrock is usually less pervious than the overburden, perched water is often found above bedrock. Coarse sediments are often found just above bedrock. Even cohesive residual soils above bedrock are often fractured and contain water. It is therefore important to pay attention to the bedrock interface, because it can cause difficulty in construction of shafts and inclines, as well as for mixed-face tunneling. In cold climates, seepage water will form ice and icicles, which can be hazardous when falling, especially into shafts.

(6) *Rocks subject to dissolution*.

(a) These include limestone, gypsum, anhydrite, halite and potash, and rocks cemented with or containing quantities of these types of materials.

(b) Calcite is only mildly soluble in pure water, but meteoric water contains carbon dioxide from the air, which forms carbonic acid in the water, able to dissolve calcite. Thus, water flowing through fractures in limestone over time can remove portions of the calcite, leaving open fissures or cavities, even caves behind. Larger cavities tend to form where joints or faults intersect. If near the surface, such dissolution can eventually result in sinkholes. Karstic landscapes are limestone regions with advanced dissolution, where pinnacles of limestone remain and where essentially all water flow is through underground caverns rather than in rivers on the surface. Examples are found in Kentucky, Puerto Rico, and Slovenia. Clearly, tunneling through limestone with water-filled cavities can be difficult or even hazardous. On the other hand, limestones that have never been subject to dissolution can be most ideal for tunneling, being easy to excavate yet self-supporting for a long time.

(c) Formation water often contains much more carbon dioxide than meteoric water and is thus able to contain more calcite in solution. This carbon dioxide comes from sources other than rain infiltration, such as oxidation of underground organic materials. If formation water containing excess carbon dioxide is released to the atmosphere at normal pressure, carbon dioxide is released from the water to form a new equilibrium with carbon dioxide in the air. Hence, calcite is precipitated as a sludge that can harden when exposed to air. This occasionally results in a clogging problem for tunnels and other underground works that incorporate permanent drainage systems.

(d) Underground works for USACE projects rarely encounter halite or other evaporites. These are most often exposed in salt or potash mines or, for example, in nuclear waste repository work such as the Waste Isolation Pilot Project in New Mexico. If drainage occurs into underground works in or near such geologic materials, rapid dissolution can result, causing cavities behind tunnel linings and elsewhere and instability of underground openings. Shafts through or into these materials must be carefully sealed to prevent water inflow or contamination of groundwater.

(e) Some geologic materials are cemented by soluble materials such as calcite or gypsum, existing either as interstitial cement or as joint fillings. Gypsum is dissolved rapidly by moving formation water, while calcite is dissolved more slowly. The San Franciscito Dam in southern California failed largely because groundwater flow resulting from the impoundment of water behind the dam dissolved gypsum cement in the rocks forming the abutments of the dam. In such geologic materials, underground structures should be made watertight.

(7) *Thermal water*. Hot springs occur at numerous locations in the United States, in all of the states from the Rocky Mountains and westward, in the Ozarks in Arkansas, and in a narrow region along the border of Virginia and West Virginia. The source of the hot water is either

meteoric water that finds its way to deep, hot strata, or the water is magmatic, or a mixture of the two. The hot water finds its way to the ground surface, helped in part by buoyancy, through preferred pathways such as faults or fault intersections. The hot water often contains minerals in solution. Apart from the obvious problems of dealing with large quantities of hot water underground, the water is also difficult to dispose of in an environmentally acceptable fashion.

*d. Analysis of groundwater inflow.*

(1) Groundwater causes more difficulty for tunneling than any other single geologic parameter. Groundwater inflow is one of the most difficult things for tunnel designers to predict, yet many decisions to be made by the designer as well as the contractor depend on reasonable assessments of groundwater occurrence, inflow, and potential effects. Inflow predictions are needed for at least the following purposes.

(a) *Leakage into or out of permanent structures*. Decisions regarding choice of lining system depend on an assessment of leakage inflow.

(b) *Groundwater control during shaft sinking*. Often the overburden and the uppermost, weathered rock will yield water that must be controlled to prevent instability, excessive inflow, or quicksand conditions. Deeper, pervious strata may also offer insurmountable problems if water inflow is not controlled. Decisions must be made concerning the control of water inflow. Water can be controlled by construction of slurry walls, grouting, freezing, installation of wells, or a combination of these methods.

(c) *Groundwater control during tunneling*. Decisions must be made regarding whether probing ahead is required in some or all reaches of the tunnel, whether dewatering or grouting in advance or from the tunnel face will be required, or perhaps whether an alternate route might be better in order to avoid high-water inflows.

(d) *Pumping requirements*. A reasonable estimate of water inflow must be made so that the contractor can acquire appropriate pumping and dewatering equipment. This is especially important when driving a tunnel downgrade or from a shaft. Water inflow also affects tunnel driving rates, whether by tunnel boring machine (TBM) or blasting.

(e) *Environmental effects*. It is often necessary to estimate the extent of water table drawdown, temporary or permanent, for reasons of environmental protection (protection of groundwater to sustain vegetation or of groundwater rights).

(2) These impacts can affect the requirements of groundwater flow analyses to estimate of the maximum expected flow rate and volume. Pump-size estimates may be the end result of groundwater inflow calculations. Conservative estimates may be appropriate for design purposes; however, overly conservative calculation may impact costs (since cost is affected by the chosen method of dealing with inflow).

(3) In contrast, where environmental issues are concerned, the needs of groundwater analysis can have a qualitatively different impact on the project. If the source of water affected by tunnel dewatering is a surface water system of environmental significance, the calculated volumes and disposal methods can affect the basic feasibility of the project. For example, increasingly stringent requirements for wetland protection can affect any project in which a significant fluctuation in the groundwater level is anticipated. If the dewatering program is calculated to produce a significant drawdown in a wetland, the precise calculation of withdrawal rates is important. The viability of a project can, in principle, rest on the ability to demonstrate that the project will not significantly affect the prevailing hydrologic regime.

(4) As a result, the designer may be faced with the need to reconcile very different requirements and to apply sophisticated techniques to obtain the necessary estimates of groundwater behavior. The methods of control can also vary, depending on the situation. Pumping or draining may not be adequate as control measures if the impact on the surrounding hydrogeologic system is to be minimized. Measures to prevent or mitigate the inflow of water to the tunnel may be required instead of pumping.

*e. Modeling of groundwater flow.*

(1) The basic principles that govern the choice of methods for groundwater flow estimation requires that the designer identify a conduit for flow (a fracture network or inherent permeability), a source of water (entrained in the rock or available elsewhere), and a gradient (determined by suitable boundary conditions and permeability of the rock medium). These requirements imply that the geometry of the system, the characteristics of the matrix, and the available sources of water must be identified. It is impossible to assess all of these for the reasons discussed above. Therefore, uncertainty will be associated with groundwater-flow estimation. Reducing this uncertainty to acceptable limits is a desirable objective, but generally a difficult if

not impossible one to achieve. This is because uncertainty lies not only in the physical system, but in the method of analysis.

(2) The physical system can only be approximated. Even though geotechnical and geophysical techniques can supplement direct observation to produce better estimates of the physical characteristics of the rock matrix, the present state of the art in geologic interpretation does not permit perfect knowledge of that matrix. The fracture network has a random component; permeability is a variable; and the location of connected water bodies as well as the recharge of those bodies are not perfectly quantifiable. As a result, even though extensive testing can produce reasonable estimates of the rock hydrogeology, those estimates are, at best, imperfect.

(3) Even the mathematics of groundwater flow are not perfectly known. It is usually assumed that Darcy flow applies, i.e., that flow is directly proportional to gradient. This is a reasonable approximation for water in a porous medium such as a sand. However, for media where fractures govern, the characteristics of flow often depart from the Darcy assumption.

(4) The sequence of analysis will depend on the specific problem, but should generally have the following characteristics:

(a) *Define the physical system*. Principal rock and conduit characteristics must be identified. Aquifer and aquiclude units and conduits or irregularities should be located. Since the scale of the problem affects the area of the physical system that is of interest, some approximating formulae or methods of analysis may be appropriate at this stage. Given this starting point, the extent of the physical system can be estimated, and characteristics within that extent can be defined.

(b) *Determine governing boundary conditions*. Water bodies, aquicludes, or other factors limiting the propagation of changes in the hydraulic gradient induced by tunneling must be determined. Since this step is closely related to the definition of the physical system, determination of boundary conditions should be done in concert with the definition of the rest of the physical system.

(c) *Identify characteristic hydrogeologic flow system*. The way the system behaves in terms of hydraulic flow patterns (fracture flow, permeable matrix flow, etc.) must be identified based on the known physical system, boundary conditions, and approximations of hydrogeologic parameters.

(d) *Estimate of hydrogeologic parameters*. Estimates of system geometry, permeability, source volumes, and similar factors that govern flow within the system must be made. At this point, the parameters of interest will depend on the physical system that has been defined. In a medium treated as porous, permeability will be important. In a medium with fractures that might be principal flow conduits, hydraulic conductivity may take on other meanings.

(e) *Select method of analysis*. Given the defined hydrogeologic problem, a model or models should be selected. The analysis, including model calibration, validation of model performance, generation of results, and testing of sensitivity can then proceed. A large number of commercially available and public-domain computer codes are available for two- or three-dimensional (2- or 3-D), steady-state, and transient flow analysis. Sometimes, simple closed solutions will have sufficient accuracy.

(5) An important part of the analysis process is to verify that the initial selection of model boundaries was adequate. If the simulated results indicate that artificial boundary conditions are being generated, then the extent locations of boundaries must be revisited. Indications of this are contour lines bending at the perimeter of a mathematical model or fixed boundaries generating large quantities of flow. Further checks should be made in terms of the estimates of volume loss. The processes that govern recharge in the system should be checked to verify that simulated rates of withdrawal are sustainable. If the model predicts a long-term loss rate greater than natural recharge over the extent of the system (e.g., from rainfall or other factors), then the model results must be checked.

*f. Simplified methods of analysis*.

(1) It is important to distinguish between different types of groundwater inflow. Depending on the character of the water source, field permeability data can be applied to flow equations for predictive purposes. The types of inflow can be classified as follows:

- Flow through porous rock.
- Flow through fractures in otherwise impervious rock.
- Flow through shatter zone, e.g., associated with a fault.
- Flow from an anomaly, such as a buried river valley, limestone cave, etc.

(2) Each of these types of flow require a different approach to arrive at reasonable groundwater inflow estimates. In most cases, however, a set of simple equations may be adequate for analysis.

(3) Flow through porous rock, such as a cemented sand or an unfractured sandstone, is reasonably regular and predictable. In such rocks, the permeability of the rock mass is a reasonably well-defined entity that can be used with confidence in analyses. The reliability of any prediction can be judged on the basis of the uniformity or variability of permeability data from field tests. In stratified materials, the permeability of the material is likely to be greater in the direction of the bedding than across the bedding. This affects not only the inflow prediction but also the borehole permeability data interpretation that is the basis of prediction.

(4) Porous rocks often have a large pore volume (10-30 percent or more) and thus contain a substantial reservoir of water that will take time to drain. In fractured rock of low porosity and permeability, water flows through the fractures, which are usually of variable aperture, have a variety of infillings, and appear in quantity and direction that can be quite random or regular, depending on the characteristics of the jointing patterns. As a result, the permeability of the rock mass is poorly defined, likely to be highly variable and scale dependent, and with unknown anisotropy; the permeability measured in the field is usually a poor representation of the actual nature of the flow of water. However, an interpretation of the data can be made in terms of equivalent permeability and geometry and used in an appropriate formula to obtain approximate results.

(5) Typically, fractured rock offers only a small storage volume. Therefore, water flows often reduce drastically in volume after a short while, unless the fractured rock aquifer has access to a larger reservoir. On rare occasions, a rock mass features porous flow and fracture flow of about equal equivalent permeability.

(6) A common occurrence is inflow through a zone of limited extent, such as a shatter zone associated with a fault, or a pervious layer in an otherwise impervious sequence of strata. With permeability measurements available and a reasonable estimate of the geometry, inflow estimates can be made using one of the equations for confined flow.

(7) Inflow from large anomalies must be judged and analyzed on a case-by-case basis. Theoretically, flow through caverns or caves can be analyzed the same way as channel flow. In practice, however, the data are not available to perform these types of analyses. In any event, the mere presence of these types of anomalies with large quantities of water will require remedial measures of one kind or another, and a precise estimate of the potential inflow is not necessary.

(8) It is a common experience that water inflow into a tunnel decreases with time from the initial burst of water to a steady-state inflow rate of only 10-30 percent of the initial inflow rate. Steady-state flow equations can be used to determine inflows based upon assumed boundary conditions. These boundary conditions will change with time, as the groundwater reservoir is depleted. It is possible to obtain a rough estimate of the decreasing rate of flow using the steady-state equations, based on estimated geometric extent and porosity of aquifer reservoir. This method will only yield order-of-magnitude accuracy. If available data warrant greater accuracy of the analysis, transient flow can be estimated using numerical analyses.

(9) A number of problems can be analyzed using the flow net method. Flow nets are graphical solutions of the differential equations of water flow through geologic media. In a flow net, the flow lines represent the paths of water flow through the medium, and the equipotential lines are lines of equal energy level or head. The solution of the differential equations require these two sets of curves to intersect at right angles, when the permeability of the medium is isotropic and homogeneous. Detailed instructions of how to draw flow nets are not presented here. Such instructions can be found in a number of textbooks. The flow net method is suitable for solving problems in 2-D, steady-state groundwater flow. Anisotropy of permeability can be dealt with using transformations, and materials of dissimilar permeability can also be modeled. The method produces images of flow paths and head and can be used to estimate flow quantities, gradients, and pressures, and to assess effects of drainage provisions and geometric options. The example shown in Figure 3-1 demonstrates its use as a means to estimate the effect of drains on groundwater pressures on a tunnel lining. The flow net is hand drawn, crude, and flawed, yet provides information of sufficient accuracy for most purposes. In addition to the flow path and head distribution, the figure shows the estimated hydrostatic pressure on the lining with drains as shown. The water flow can be estimated from the number of flow channels, $n_f$, and the number of potential drops, $n_d$, together with the total head $h$:

$$q = khn_f/n_d$$

*g*. *Limitations of simplified methods of analysis*.

(1) The differential equations governing groundwater flow are not inherently complex, but are of a form that do not readily lend themselves to direct solution. As a result, analytic solutions to groundwater flow problems are generally derived for special simplified cases of the general problem. These simplifications generally take the form of assuming homogeneous and/or isotropic media, tractable boundary conditions, steady-state conditions, and/or simplified source/loss terms. Literally dozens of such special case solutions exist, and they have been used in a variety of problems.

(2) Anisotropy and other complicating factors are the rule rather than the exception; therefore, simplified methods must be used with caution. The assumed range of influence in a well function, for example, is commonly seen as a characteristic of the medium and the withdrawal rate. In fact, in the long term this factor represents the distance to a boundary condition that limits the extent to which drawdown can occur. A well function drawdown equation, however, can provide a useful approximation of events under some conditions. Given the ready availability of a number of mathematical models that provide easy access to better solutions, analytic solutions have their place in analysis for tunnels and shafts in two main areas. They can be used to provide a useful order of magnitude check on model performance to verify the basic model behavior and as first-cut approximations that help in problem definition during the basic steps in analysis described above.

(3) At present, the state of the art of computer simulation using finite element or finite difference techniques has progressed to the point where these models are relatively easily and effectively applied. Although use of such models in a complex 3-D system can present a challenge, the models when properly applied can be used with confidence. Errors may result from either the uncertainty in measurement of the physical system or, as noted above, from inappropriate assumptions as to the mechanics of flow in the system. These errors are common to all of the above methods. The use of a comprehensive finite model, and not analytic solutions or flow nets, will reduce errors introduced by simplification of the physical system to a minimum.

(4) An important part of the process of analysis lies in the recognition of the basic nature of flow in fractured rock systems. If the physical system can be approximated as a continuum in which Darcy's law applies (i.e., a porous medium), such as a sand or sandstone, the problems of analysis are relatively straightforward.

(5) In a fractured medium, the fractures that dominate flow can be approximated as a continuum system with a permeability and porosity representing the net effect of the fracture system. This assumption is appropriate, provided that no single or limited number of fractures dominates and that the hydraulics of flow can be represented by an approximating medium in which the average effect of a large number of randomly placed and interconnecting fractures can be represented by an average effective hydraulic conductivity. This approach may be reasonable provided that the system is such that flow is approximately proportional to gradient, and flow is not dominated by a small number of fractures.

(6) Most difficult is the case where fractures are large and randomly placed. As observed above, in such a system the permeability of the rock mass can be overwhelmed by the conductivity of a single channel, which provides a hydraulic conduit between the source of water and the tunnel. Even if it is known for certain when such a fracture will be encountered, the hydraulics of flow can be difficult to establish. Effective conduit size, length, section, and roughness, which all have an impact on flow rate, can be highly variable.

(7) Given that the likelihood of encountering such a fracture often can only be estimated, the size of the required pumping system can be difficult to establish. If available pressure head is known, and the approximate section of a fracture can be estimated, then the hydraulics that govern the flow can be estimated by taking an equivalent hydraulic radius, section, and roughness. If these parameters are treated as random variable analysis and a statistical analysis is performed to produce a variability for each of these factors, confidence limits can be determined.

(8) Alternatively, calculating flow for a range of critical sizes and hydraulic characteristics can produce estimates of potential flow rates. The problem of solving for the likelihood of intersecting a particular number of independent fractures then arises. Treating the problem as one of a spatially distributed variable, it is possible to generate estimates of this occurrence provided that the fracture system has been sufficiently well characterized. In practice, the most likely compromise is to estimate the probable effective hydraulic characteristics of a fracture, estimate the rate of intersection (fractures per tunnel mile), and add a safety factor to the design of dewatering facilities.

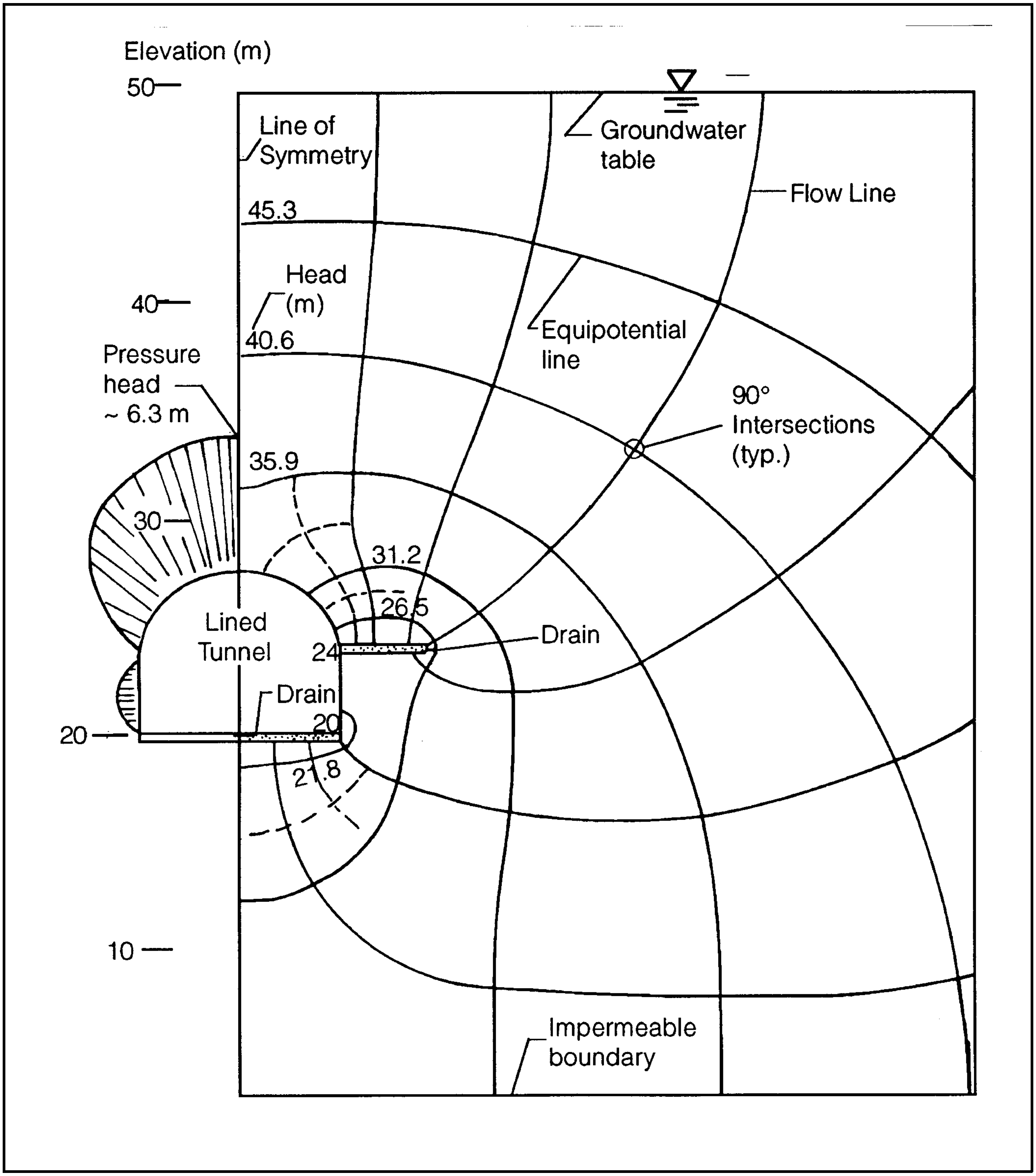


Figure 3-1. Flow net for analysis of inflow and lining pressure, tunnel in homogeneous material

## 3-6. Gases in the Ground

Natural gases are encountered rarely in tunneling. However, when natural gases enter tunnels and other underground openings, they pose a particularly severe hazard that can, and often has, resulted in death to workers. Gases are often found in unexpected areas and are difficult to detect, unless monitoring stations are set up for the purpose. It is necessary, therefore, to determine during design the risk of encountering gas during construction, so that appropriate measures can be taken to eliminate the hazards of gas exposure. A specific effort should be made during the explorations phase to determine the risk of encountering gas during construction and to classify the works as gassy, potentially gassy, or nongassy. This effort should include research into the history of tunneling in the particular geographic region, interpretations of the geologic and geohydrologic setting, measurement of gas content in air samples from boreholes, geophysical methods to assess the existence of gas traps in the geologic formations, and other methods as appropriate. To aid in the planning and execution of such explorations and interpretations, the following subsections describe briefly the origin and occurrence of various gases in the subsurface. Safety aspects of gas in underground works are further discussed in Section 5-11.

*a*. *Methane gas*.

(1) *General*. Of all the naturally occurring gases in the ground, methane gas is the most common and has resulted in more accidents and deaths than any other gas. In the United States, occurrences and fatal accidents in civil engineering tunnel projects have been reported, among others, in the following localities:

- Los Angeles Basin (occurrence in a number of water and rapid transit tunnels, fatal explosion in the San Fernando water tunnel at Sylmar, 1971).

- Port Huron, Michigan (accident in sewer tunnel through Antrim Shale, 1971).

- Rochester, New York (occurrence in sewer tunnel through Rochester Shale).

- Milwaukee, Wisconsin (accident in sewer tunnel through porous sandstone).

Other occurrences in tunnels include Vat, Utah; Richmond, New York; Euclid, Ohio; and Soliman, California. Methane emissions measured in these tunnels have averaged 2-25 l/s (5-50 cfm), with peak emissions up to 200 l/s (400 cfm) (Critchfield 1985).

(2) *Sources*.

(a) There are several sources in nature for the generation of methane gas. The most common origin of methane gas in large quantities is thermomechanical degradation of organic materials at great depth. This is a process related to the generation of coal, anthracite, and hydrocarbons, and methane gas is, therefore, often found in association with coal and anthracite strata and with oil fields. Coal mines are frequently affected by steady inflows and occasional outbursts of methane (coal can contain a volume of 10 $m^3$ of methane per $m^3$ of coal), and methane is a common byproduct of crude oil production. Other volatile hydrocarbons usually accompany the methane.

(b) Another source of methane gas is near-surface bacterial decay of organic matter in sediments with low-oxygen environment, such as in peats and organic clays and silts, and in marshes and swamps with stagnant water (marsh or swamp gas). This source generally produces much smaller flow rates than sources associated with coal or oil. In glaciated environments, methane is often generated in interglacial organic deposits such as interglacial peat bogs. Methane is also generated in man-made organic landfills. Methane can also result from leakage out of natural gas and sewer lines and sewage treatment plants, and abandoned wells may provide conduits for gas flows.

(c) Knowledge of the origins of methane gas and other volatile hydrocarbons is important for the assessment of the risk of encountering gas. However, the occurrence of such gases is by no means restricted to the strata of their origin. While solid carbons will remain in place in the strata of origin, liquid hydrocarbons will flow into other strata in a manner determined by gravity, geologic structure, and strata porosity and permeability. Gas will seek a path to the ground surface through permeable strata until released at the ground surface or trapped in a geologic trap that prevents its release. Thus, gas can be found many miles away from its origin in strata that have no other traces of carbon or hydrocarbon. In fact, gas has been found in rock formations ranging from pegmatite, granite, and other igneous or metamorphic rocks to shale, mudstone, sandstone, and limestone, and in mines for copper, diamonds, iron, gold, uranium, potash, or trona. Gas is also often found in salt deposits, either dissolved in brine or as gas pockets in voids. Such gas pockets in salt under pressure sometimes cause violent outbursts when mining occurs close to the gas pocket.

(d) Geologic gas traps are formed by several kinds of geologic structures. Gas traps are commonly found in association with deformed strata adjacent to salt domes, often with liquid hydrocarbons. Fault displacements sometimes juxtapose pervious and impervious layers to create a gas trap. Folded strata also form traps, especially in anticlines and monocline. Impervious clay strata in glacial sediments can form traps for gas originating from interglacial organic deposits or deeper origins.

(e) As other gases, methane often occurs in gas form in the pores, fractures, and voids of the rock mass. Breakage of the rock or coal and exposing wall surfaces liberates the gas. However, large quantities of gas can be dissolved in the groundwater. Water can contain methane and other gases in solution in concentrations that depend on the water temperature and the hydrostatic pressure in the water. When water is released into an underground opening, the pressure drops drastically, and the ability of the water to contain gases in solution virtually disappears. Hence, the gases are released into the tunnel in quantities that are proportional with the amount of water inflow.

(3) *Levels*. Methane is lighter than air (density 55 percent of air) and in stagnant air tends to collect in air traps in underground works. When mixed, however, it does not segregate or stratify. Methane is explosive in mixtures of 5 to 15 percent. In general, the methane level should be kept below 0.25 percent, and a methane content above 1 percent is usually unacceptable.

(4) *Construction*. Construction in the presence of toxic, flammable, or explosive gases is regulated by OSHA (29 CFR 1926). Guidance can also be found in MSHA (30 CFR 57). Some states have stricter rules, such as the State of California's Tunnel Safety Orders. Minimum requirements and provisions for dealing with flammable or toxic gases are presented in the California Tunnel Safety Orders, as well as in OSHA (29 CFR 1926).

(5) *Classifications*. These Safety Orders classify tunnels as follows:

(a) Nongassy classification shall be applied to tunnels where there is little likelihood of encountering gas during the construction of the tunnel.

(b) Potentially gassy classification shall be applied to tunnels where there is a possibility flammable gas or hydrocarbons will be encountered.

(c) Gassy classification shall be applied to tunnels where it is likely gas will be encountered or if a concentration of 0.25 percent by volume (5 percent of LEL [lower explosive limit]) or more of flammable gas has been detected not less than 12 in. from the roof, face, floor, and walls in any open workings with normal ventilation.

(d) Extrahazardous classification shall be applied to tunnels when the Division [of Industrial Safety] finds that there is a serious danger to the safety of employees and flammable gas or petroleum vapors emanating from the strata have been ignited in the tunnel, or a concentration of 20 percent of LEL petroleum vapors has been detected not less than 3 in. from the roof, face, floor, and walls in any open workings with normal ventilation.

*b. Hydrogen sulfide*.

(1) Hydrogen sulfide is lethal in very small quantities. Its characteristic smell of rotten eggs is evident even at very small concentrations (0.025 ppm), and low concentrations quickly paralyze the olfactory nerves, deadening the sense of smell. Hence, smell cannot be relied on, and the presence and concentration of hydrogen sulfide must be measured. The safety threshold limit for 8 hr of exposure is 10 ppm. Higher concentrations cause membrane irritation; concentrations over 700 ppm may not be survivable.

(2) Hydrogen sulfide is a product of decay of organic materials; it is often associated with the occurrence of natural gas and liquid hydrocarbons, but has also been found in swampy areas or near sewers, landfills, and refineries. It is highly soluble in water and is often carried into underground openings with water inflow, and is sometimes produced by reaction between acid water and pyrite or marcasite. It is also common in association with geothermal water and volcanic emissions.

(3) Hydrogen sulfide, like methane, is flammable or explosive in the range of 4.3- to 45.5-percent concentration in air.

*c. Sulphur dioxide and other gases*.

(1) Sulphur dioxide results from oxidation of sulphur or sulfides in sediments and in hydrothermal deposits with sulfides, or directly from volcanic action, but is encountered more commonly as a component of blast fumes, fire, and combustion engine exhaust. Sulphur dioxide is toxic with a safety threshold value of 2 ppm.

(2) Carbon dioxide derives from carbonaceous materials subject to oxidation or effects of acid water. This is an asphyxiant with a threshold level of 5,000 ppm; it is toxic above 10,000 ppm. An excess of carbon dioxide is often

associated with depletion of oxygen. Carbon dioxide is heavier than air and settles into depressions, shafts, or large drillholes for caissons or wells where asphyxiation can become a real danger. Carbon dioxide is also found in hot water from deep origins and in geologic strata.

*d. Other gases.*

(1) Hydrogen occurs occasionally in association with hydrocarbons and is explosive.

(2) Radon gas is a decay product of uranium. Radon and its first four decay products are hazardous because of their emission of alpha particles during their relatively short half-lives. These alpha particles can cause respiratory cancer. Radon is found in uranium mines, where the hazard is controlled by dilution with increased ventilation, sometimes supplemented by installation of membranes and rock coatings. Radon is also found in the pores and fractures of other rock types that contain uranium, especially metamorphic and igneous crystalline rocks such as gneiss and granite, but also in some shale beds. Groundwater contained in these types of formations also often carry radon in solution. The presence of radioactive materials can be detected by borehole probes. Radon detectors can detect the presence and activity of radon in borehole or tunnel air.